Stormwater particles and their sampling using passive devices

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ABSTRACT

Total Suspended Solids (TSS) is commonly used as a measure of particle concentration in stormwater. The breakdown of TSS into subgroups based on particle size is an important step in describing stormwater characteristics. A simple classification system is proposed that divides solids into four size ranges; Very Fine (VFPs, <8µm), Fine (FPs, 8-63µm), Medium (MPs, 63-500µm) and Coarse Particles (CPs, >500µm).

The use of passive samplers to obtain unbiased, flow-weighted samples of non-Coarse particles was investigated. Two alternative passive samplers referred to as a flow splitter and an orifice and weir device were designed, constructed and tested. The flow splitter outperformed the orifice and weir device in terms of sampling accuracy. Based on hydraulic testing up to 5 L/s, the flow splitter was able to accurately (±2% error) obtain a constant sample volume: flow volume ratio compared to a ±15% error for the orifice and weir. Based on sediment testing, the performance of the flow splitter in obtaining VFP and FP samples was similar to that of high frequency grab sampling. Samples collected by the flow splitter matched theoretical concentrations of particles less than 63µm to within ±2% error. All sampling methods significantly underestimated the concentration of particles greater than 63µm (MPs) and more research is needed in this area. Overall, the flow splitter is considered to have significant potential for determining the Event Mean Concentration of stormwater particles.

KEYWORDS

Event Mean Concentration; passive samplers; stormwater monitoring; suspended solids

INTRODUCTION

This paper is based on a current PhD research project by the author investigating the washoff of suspended particles from selected urban surfaces during storm events. The urban surfaces range from 50 to 450m^2 in area and include a road pavement, a carpark, a galvanised roof, a grassed area and a bare soil area. A key objective of the research work is to design, test and install passive samplers to obtain composite stormwater samples from each urban surface. The samples are to be analysed to determine the Event Mean Concentration (EMC) of suspended particles.

Passive samplers are not powered and rely on the physical flow of stormwater to obtain a sample. They have been used in past studies (e.g. Clarke *et al.*, 1981; Waschbusch *et al.*, 1999) to monitor runoff from urban surfaces and can be classified in terms of the main hydraulic principle that is applied in their design. These principles are gravity flow, siphon flow, rotational flow, flow splitting and direct sieving (Brodie and Porter, 2004).

This paper describes:

- A simple particle classification system that will be used in the sampling of urban stormwater. Particles are subdivided according to size and type (organic or inorganic).
- The design of two alternative passive samplers. The samplers are based on flow splitting and gravity flow principles.
- Hydraulic testing of the passive samplers to check their capability to obtain flow-weighted samples
- Sediment testing of the passive samplers to determine their performance in obtaining representative samples of the adopted particle size classes. As a comparison, grab sampling was also employed during the sediment tests.

PROPOSED PARTICLE CLASSIFICATION SYSTEM

Standard TSS analysis provides a single measure of the total mass of organic and inorganic particles. As TSS is a weight-based measure, the presence of a relatively small number of large particles can influence the overall TSS concentration. A stormwater sample containing some coarse particles may theoretically have the same TSS concentration as a sample dominated by fine particles, but the physical properties (e.g. turbidity), water quality characteristics and ability to be treated would be very different. Discussions on the reliability of TSS as a suitable measure for stormwater particles can be found in James (2003) and URS (1999).

Washoff behaviour, contaminant associations such as heavy metal adsorption and stormwater treatment processes are closely allied with particle size. Organic particles exhibit different physical (e.g. tend to be less dense) and biochemical properties compared to inorganic particles. Due to this heterogeneity, the breakdown of stormwater particles into various subgroups is considered to be an important step in characterising stormwater runoff.

Various researchers have previously separated TSS into individual particle size ranges as part of their urban stormwater studies. Examples of particle classifications are provided in Table 1. Currently there is no consistent approach to dividing TSS into particle size classes, which makes data comparisons very difficult.

Table 1. Examples of particle classifications used for urban stormwater

Source	Description of Particle Classification
Ball *et al.* (1994)	Three size classes; 0.45-37µm, 37-62µm, >62µm
Characklis & Wiesner (1997)	Three size classes; < 0.45µm, 0.45-20 µm, > 20µm
Madge (2004)	Five size classes; <0.4µm, 0.4-5µm, 5-20µm, 20-80µm, >80µm

Table 2 shows a particle classification system that will be used by the author as a basis to evaluate stormwater runoff from urban surfaces. It divides suspendable particles according to size into four classes; Very Fine, Fine, Medium and Coarse. Each class is further subdivided into its organic and inorganic fractions, yielding a total of eight particle subclasses.

Table 2. Proposed particle classification for urban stormwater sampling

Particle Class	Size Range (µm)	Inorganic Particles	Organic Particles
Very Fine (VFPs)	0.45 – 8	Very Fine Inorganic Particles (VFIPs)	Very Fine Organic Particles (VFOPs)
Fine (FPs)	8 – 63	Fine Inorganic Particles (FIPs)	Fine Organic Particles (FOPs)
Medium (MPs)	63-500	Medium Inorganic Particles (MIPs)	Medium Organic Particles (MOPs)
Coarse (CPs)	>500	Coarse Inorganic Particles (CIPs)	Coarse Organic Particles (COPs)

The design objective of the passive samplers is to obtain representative samples of the non-Coarse particles in urban stormwater (i.e. Very Fine, Fine and Medium classes). Features of these particle classes are outlined in Table 3. Approximately an 8-fold increase in particle size defines the boundary of each class. With the exception of Very Fine silt, which is included in the Very Fine class, the classes can be separated as clays, silts or sands under the system described by Bent *et al.* (2001). The upper size limit for Fine particles is consistent with that specified by ASTM (2002) for ‘fines’ sediment concentration in water.

Table 3. Features of the proposed particle classification system (non-coarse only)

Feature	Very Fine	Fine	Medium
Upper limit of particle size	8 µm	63 µm (7.9 x VFP limit)	500 µm (7.9 x FP limit)
Corresponding grain sizes in particle class	Fine clay, Medium clay, Coarse clay, Very Fine silt	Fine silt, Medium silt, Coarse silt	Very Fine sand, Fine sand, Medium sand

The proposed classification system assumes that suspended particles consist of non-Coarse particles smaller than 500 µm. Dense mineral particles generally only remain in suspension if smaller than sand (<63 µm), but sand-sized particles can be temporarily suspended by flowing waters (Davies-Colley and Smith, 2001). Medium sand (500 µm maximum size) may be considered to be an upper limit for suspended matter as larger particles tend to be conveyed in stormwater as bedload (Lloyd and Wong, 1999). This definition of suspended matter has also been used in the performance testing of stormwater treatment devices (e.g. Washington State, 2002).

DESCRIPTION OF PASSIVE SAMPLER DESIGNS

Two types of passive sampler were designed, constructed and tested. A flow splitter device is described in a previous paper by Brodie and Porter (2004). As an alternative to the flow splitter, a gravity flow sampler based on an orifice and weir arrangement was developed.

Both samplers were designed to continuously extract a sample over the full duration of a storm event. In order to obtain representative EMCs of stormwater particles, the ratio of the sample discharge to the stormwater discharge should ideally be constant during the event. That is, the sample flow volume ratio (abbreviated in this paper as SFVR and defined as the ratio of the sample volume to the stormwater volume passing the device) should also be a constant value.

Flow Splitter

A diagram of the flow splitter installed in a rectangular channel is provided as Figure 1. A slot parallel to the flow direction is located in the channel bed. Vertical walls either side of the slot splits the stormwater flow into a smaller channel fitted to the underside of the channel, thus forming the main flow splitter. The sample discharge that is obtained is in proportion to the ratio of the splitter gap (i.e. gap between the vertical walls) to the width of the channel. A secondary flow splitter is housed within the smaller channel to further split off a portion of the stormwater flow. By adjusting the gap widths of the main and secondary splitters, a wide range of SVFRs can be achieved by the device.

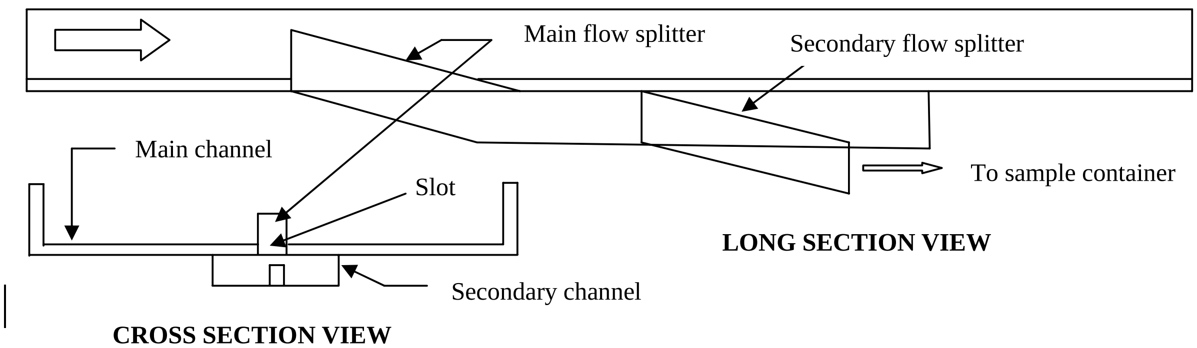

Figure 1. Diagram showing the cross section and long section views of the flow splitter

Orifice and Weir

A diagram of the orifice and weir is presented in Figure 2. This device incorporates an orifice located on the side wall of the rectangular channel to drain off a continuous sample from the stormwater flow. A downstream weir, consisting of two rectangular side plates, acts as a flow constriction and regulates water depth and hence flows into the orifice. This alternative design was investigated as the sample extraction point is located at the side of the channel. It was considered that this approach could potentially be less prone to debris blockage compared to the flow splitter, which is centrally located within the channel.

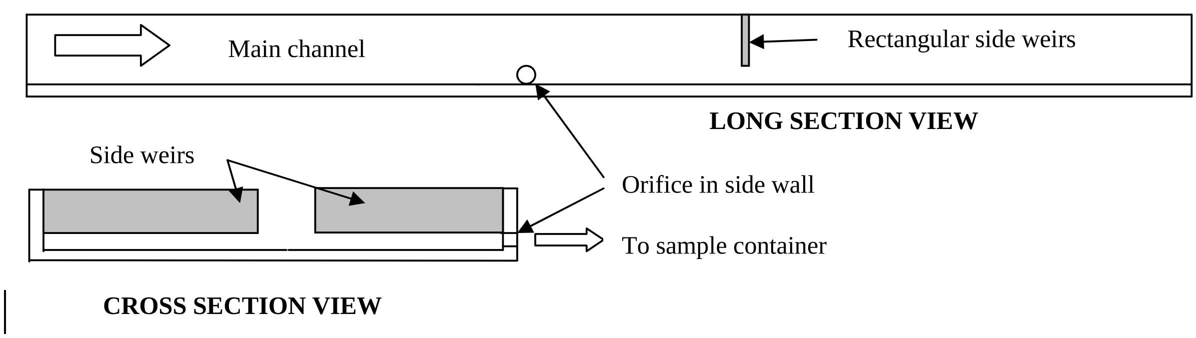

Figure 2. Diagram showing the cross section and long section views of the orifice and weir

HYDRAULIC TESTING OF PASSIVE SAMPLERS

Hydraulic Testing Methods

Prototypes of both types of samplers were constructed for hydraulic testing. The prototype design aimed to achieve a SFVR of approximately 1:200. The passive samplers were tested in a hydraulic laboratory under steady-state discharges ranging from 1.0 to 5.0 L/s. Separate test runs were conducted for each device. Water was pumped into a 150mm-wide rectangular channel which housed the sampler and a series of test runs were made at 0.5 L/s increments. An electronic flow meter was used to measure the water discharge and to check that constant flow conditions were maintained.

A plastic container collected the flow extracted by the sampler and the time to fill the container and the sample volume were recorded. SFVRs were then calculated for each test run. During the testing program, modifications were made to both samplers to improve their hydraulic performance.

Hydraulic Test Results and Discussion

Experimentally determined SVFR values for the flow splitter fell in a narrow range from 1:174.6 to 1:184.1 (mean 179.4±3.0), consistent with a relatively constant SVFR that is needed to obtain accurate EMC data. By comparison, the SFVR values for the orifice and weir ranged widely from 1:114.5 to 1:191 (mean 153.2±24.5). If used for collecting EMC samples, the potential sampling error in the orifice and weir device would be of the order of ±15% compared with ±2% for the flow splitter.

SEDIMENT TESTING OF PASSIVE SAMPLERS

The efficacy of the two types of passive samplers in capturing representative concentrations of suspended particles was also evaluated. A sediment testing rig was established to simultaneously test the flow splitter and the orifice and weir device. Grab samples at the outlet of the testing rig were taken for comparative purposes. The testing investigated non-Coarse particles (MPs, FPs and VFPs as defined in Table 2) and a total of three test runs were performed.

Sediment Testing Methods

Sediment Testing Apparatus. A diagram of the testing apparatus, which was set up outdoors adjacent to a small dam, is shown in Figure 3.

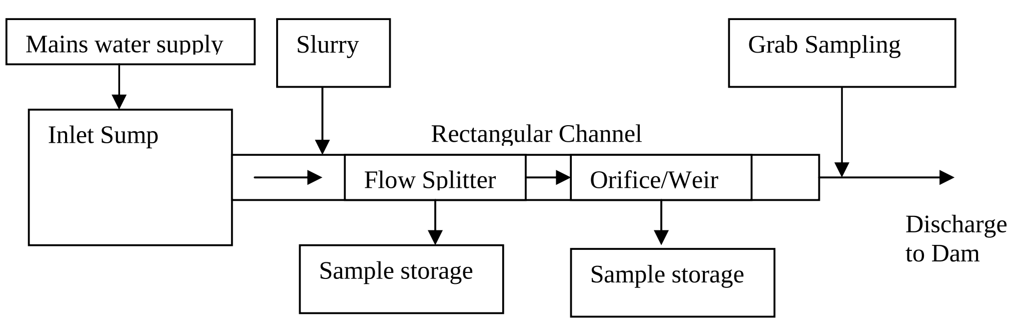

Figure 3. Diagram showing the layout of the sediment testing apparatus

A slurry mixture of soil and water was continuously added to the channel flow at a location just downstream of the inlet sump. The slurry was contained in a 60L drum and was released by a small tap. Sample flows from the two passive samplers were captured by 20L drums for laboratory analysis.

Sediment Testing Procedures. A constant water flow into the channel was maintained at a discharge of approximately 3 L/s. Sample collection drums were placed under the two passive devices when the slurry discharge into the channel was initiated. During the test, the contents of the slurry drum were manually mixed by using a churn. At one minute intervals, a 1L grab sample was taken at the channel outlet. These samples were added together to provide a composite sample of the test. When the slurry drum was fully drained, grab sampling and sample capture by the passive devices also ceased. The elapsed time to empty the slurry mixture into the channel was recorded. Three composite samples from the flow splitter, the orifice and weir, and grab sampling were obtained for laboratory analysis.

Laboratory Procedures. Laboratory analysis involved the measurement of particle concentrations in the prepared slurry and the samples collected during the sediment test runs.

A slurry mixture was prepared before each sediment test run. Slurry preparation involved mixing 500g dryweight of a blacksoil material with ~40L of mains water, producing a suspended particle concentration of ~13,000 mg/L. The slurry was mixed and stored for a minimum of three days to ensure wetting of the soil particles. After remixing, determinations of MP, FP and VFP concentrations in the slurry mixture were made. Generally, each slurry mixture was dominated by particles less than 63µm (i.e. FPs and VFPs) representing 85% to 92% of the total particle mass.

The slurry was wet-sieved through a 500µm screen to remove Coarse particles (CPs), followed by a 63µm screen to retain MPs. MP concentration was determined by drying and weighing as per ASTM (2002). The dried MPs were returned to the slurry mixture. FP and VFP concentrations involved a sequential filtration procedure that used cellulose filter paper (8µm rating) and glass fibre filters. These screening and filtration procedures were also used in the analysis of the sediment test samples.

Sediment Test Results and Discussion

For each test run, theoretical estimates can be made of the particle concentrations following dilution of the slurry within the channel flow. The theoretical concentrations, given in Table 4, were derived from the measured particle mass in the slurry, the elapsed duration of the test and the steady state channel discharge. For Run 3, the VFP concentration was significantly higher than previous runs and this was due to sonification of the slurry mixture prior to laboratory analysis.

Table 4. Theoretical particle concentrations of channel flow during the sediment tests

Test Run	Particle Concentration (mg/L)			
	MPs	FPs	VFPs	Total
Run 1	32.8	104.8	65.4	203
Run 2	14.5	92.8	72.3	165.1
Run 3	20.4	66.5	173.0	259.9

After each test run, the particle concentrations (MP, FP and VFP) of the three collected samples were laboratory analysed. To evaluate the performance of each sampling technique, the particle concentrations were expressed as a percentage of the theoretical value. Statistics of these normalised values were calculated and are provided in Table 5.

Table 5. Sediment test statistics normalised as a percentage of theoretical particle concentrations

Particle Class	% of Theoretical Concentration (Mean ± Standard Deviation)		
	Grab	Flow Splitter	Orifice & Weir
MPs	25 ± 23	29 ± 11	31 ± 24
FPs	91 ± 34	85 ± 42	84 ± 36
VFPs	122 ± 29	129 ± 40	111 ± 43
<63µm FP+VFP	*100 ± 8*	*98 ± 2*	*91 ± 7*
<500µm MP+FP+VFP	*88 ± 11*	*91 ± 6*	*84 ± 10*

It is assumed that the percentage mean provides a measure of sampling accuracy; that is, the capability of matching the theoretical particle concentration. Also, the percentage standard deviation indicates the consistency of sampling performance over the range of test runs. On this basis, the sediment test statistics in Table 5 indicate that:

- All sampling methods significantly underestimated the concentration of Medium Particles (MPs). These sand-sized particles are unlikely to be evenly distributed across the channel bed, making accurate sampling very difficult. In addition to this spatial variability, the poor performance of the relatively frequent grab sampling suggests that there are also significant temporal fluctuations in the movement of MPs within the channel. The relatively low mass of MPs in the slurry mixture may have also introduced inaccuracies during laboratory analysis.
- All sampling methods gave lower FP and higher VFP concentrations relative to the theoretical values. As the concentrations for the different sampling methods were of similar magnitude, it was considered that this outcome may be due to the filtration of the highly concentrated slurry mixture. In particular, filter blockage may be a source of error affecting the theoretical concentration estimates.
- As a result of uncertainty in the theoretical values, the combined sum of FPs and VFPs (FPs + VFPs in Table 5) was introduced as a measure of sampling performance. This sum represents particles smaller than 63µm. Grab sampling was a highly accurate method, closely followed by the flow splitter, for the sampling of these particles. The orifice and weir was the least accurate method, but provides a reasonable basis of sampling (approximately 10% underestimation of theoretical concentrations). The flow splitter gave the most consistent performance over the range of test runs.
- In the case of total particles less than 500µm (MPs+FPs+VFPs in Table 5), the accuracy of the flow splitter was similar to the frequent grab sampling and is potentially a more consistent method. The orifice and weir device appears to be the least accurate method. The three methods underestimated particle concentrations by 9% to 16% and this inaccuracy was mainly introduced by the poor sampling performance for MPs.

CONCLUSIONS

Two types of passive sampler were evaluated for their performance in obtaining particle EMCs in stormwater runoff. A simple particle classification was used, dividing suspended non-Coarse solids into three size ranges; Very Fine (VFPs, <8µm), Fine (FPs, 8-63µm) and Medium (MPs, 63-500µm). The passive samplers included a flow splitter and an orifice and weir device. Based on hydraulic and sediment testing, it was found that:

- The flow splitter accuracy (± 2% error) in obtaining a flow-proportional sample was significantly better than the orifice and weir (± 15% error).
- Generally, the accuracy of the flow splitter in sampling stormwater particles was similar to frequent grab sampling and is potentially a more consistent method. The orifice and weir device appears to be the least accurate sampling method.
- In the case of sampling particles less than 63µm (FPs and VFPs), the flow splitter was highly accurate (98% match with theoretical concentrations) and is considered to be a suitable sampling method for this size range.
- All sampling methods failed to obtain fully representative samples of MPs. This poor performance was attributed to spatial and temporal fluctuations in the transport of MPs within the flow channel. More research is required in improving sampler performance in this particle size range.

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